

# SEARCH FOR SUPERSYMMETRY IN ATLAS

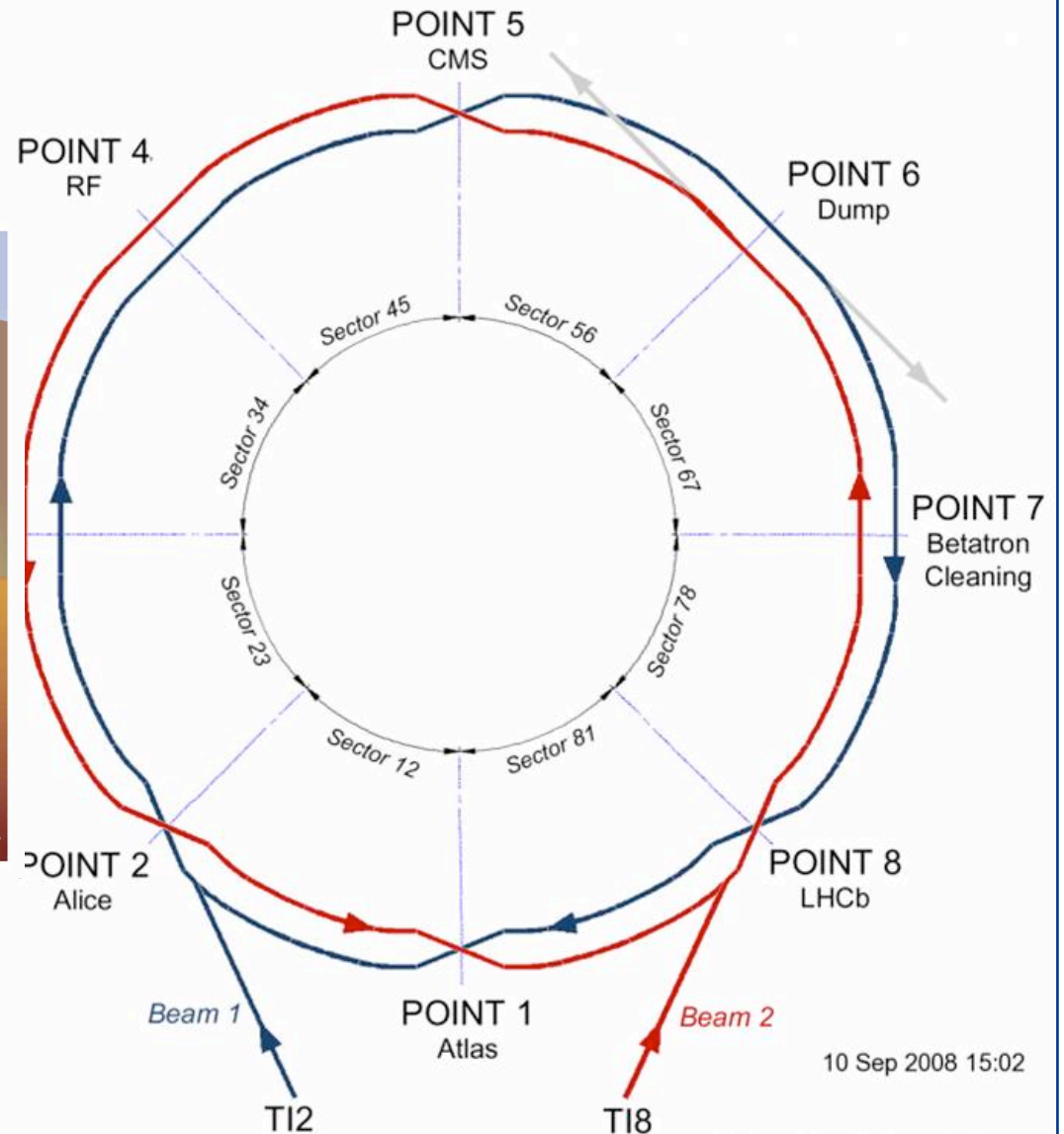
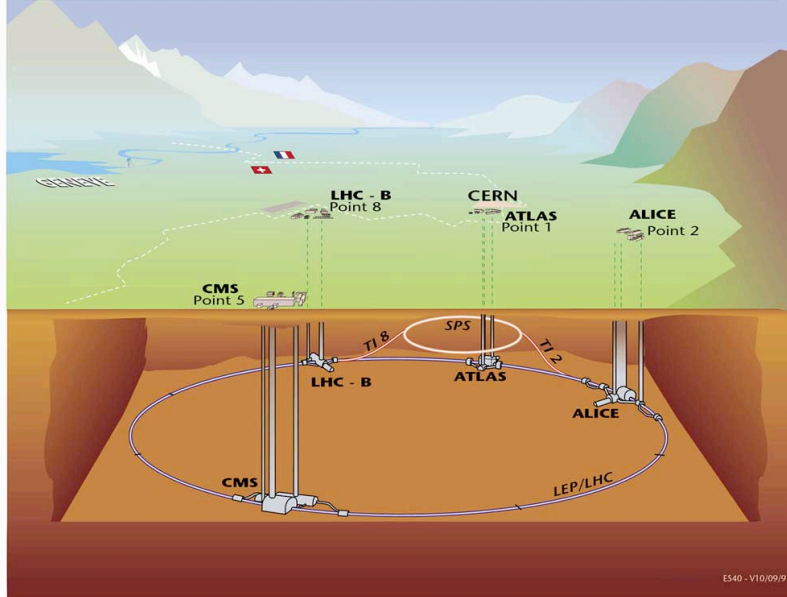
C. Clément (Stockholm University) for ATLAS  
Brookhaven Forum 2008, "From LHC to Cosmology"



# THE LARGE HADRON COLLIDER (LHC)

p-p collisions 14 TeV  
Luminosity  $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

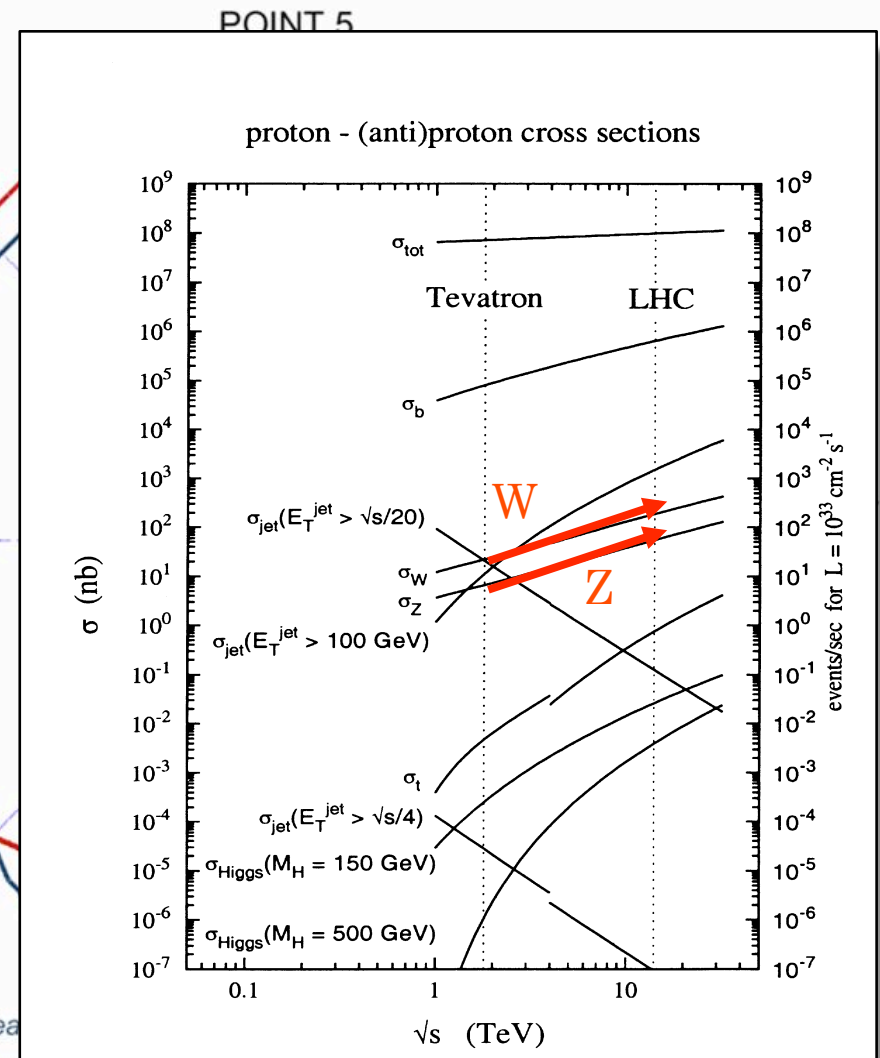
Overall view of the LHC experiments.



# THE LARGE HADRON COLLIDER

p-p collisions 14 TeV  
Luminosity  $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Process	$\sigma$ (nb)	Events ( $\int \mathcal{L} dt = 100 \text{ pb}^{-1}$ )
Min bias	$10^8$	$\sim 10^{13}$
bb	$5 \cdot 10^5$	$\sim 10^{12}$
Inclusive jets $p_T > 200 \text{ GeV}$	100	$\sim 10^7$
$W \rightarrow e\nu, \mu\nu$	15	$\sim 10^6$
$Z \rightarrow ee, \mu\mu$	1.5	$\sim 10^5$
tt	0.8	$\sim 10^4$



10 Sep 2008 15:02

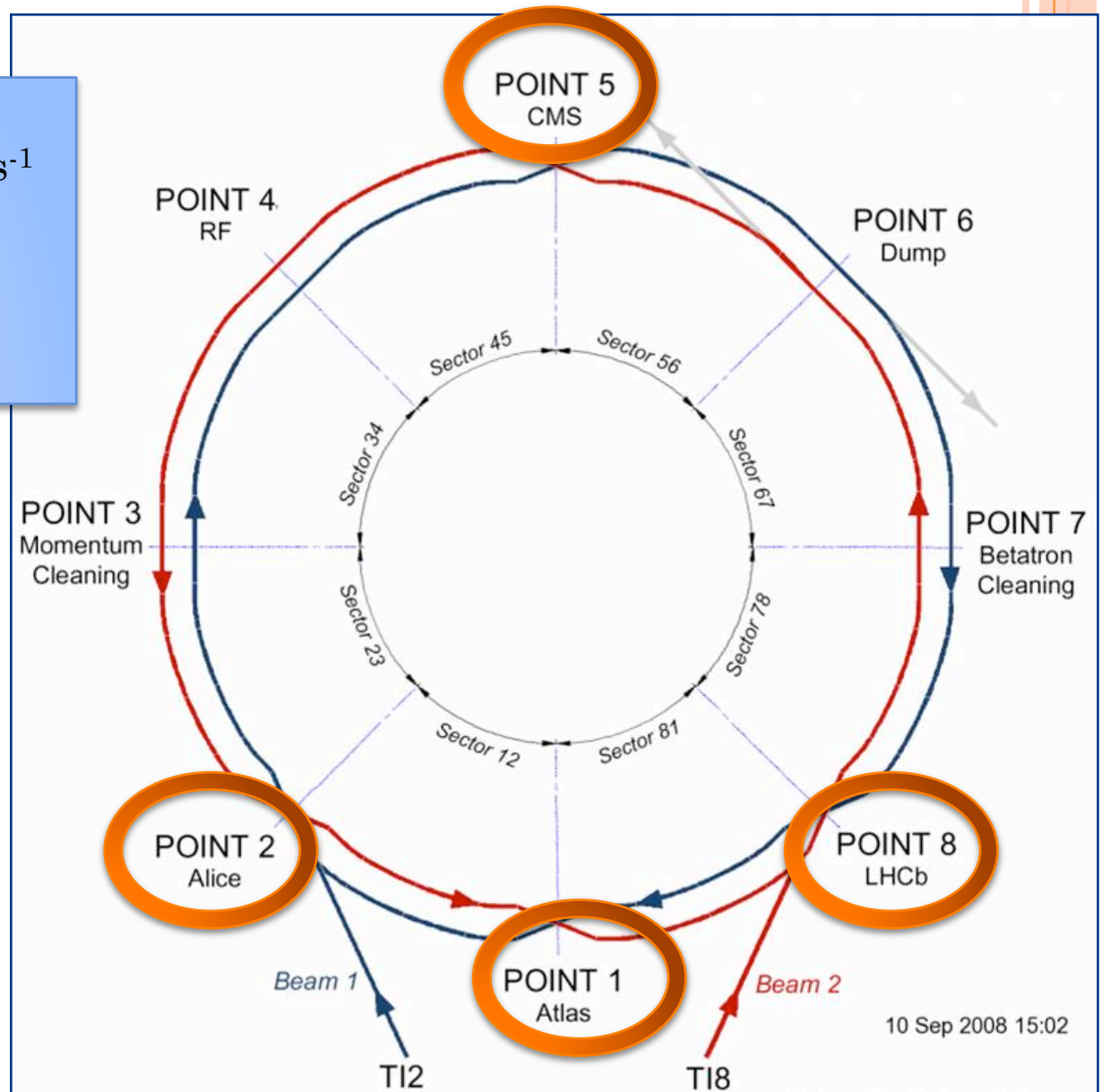
TI2

TI8

# THE LARGE HADRON COLLIDER

p-p collisions 14 TeV  
Luminosity  $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

4 experiments to explore the  
constituents of matter and  
their interaction at  $10^{-19}\text{m}$





# THE LARGE HADRON COLLIDER

p-p collisions 14 TeV  
Luminosity  $10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

4 experiments to e  
constituents of ma  
their interaction a

## Physics Motivations

Higgs boson

Solve/ postpone Hierarchy Problem by  
Producing Dark Matter in the lab  
Susy, Kaluza Klein, little Higgs ...?

TeV scale gravity?

Extra dimensions?

Heavy gauge bosons?

Quark and lepton compositeness?

??

Quark – gluon plasma

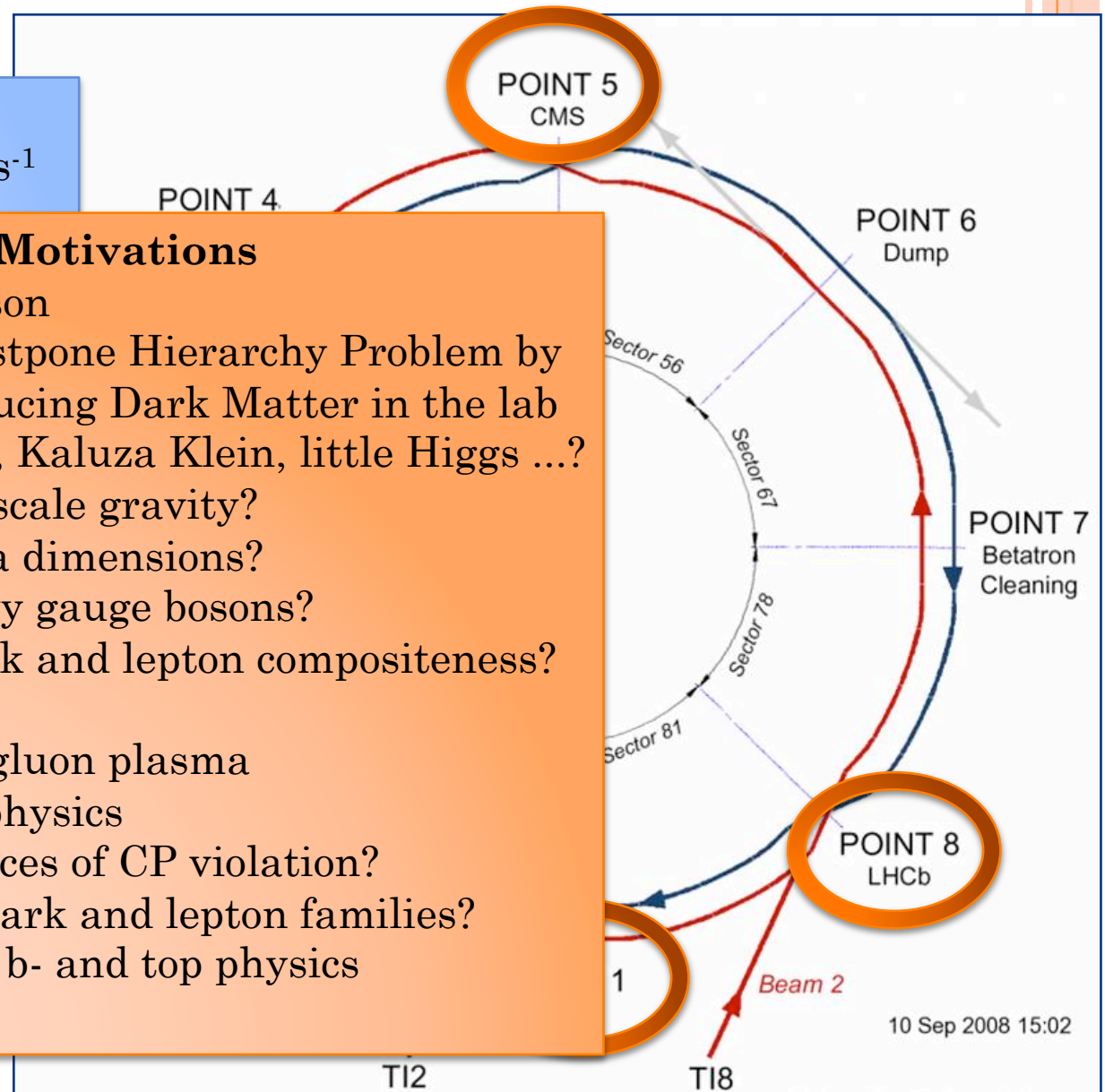
Flavour physics

New sources of CP violation?

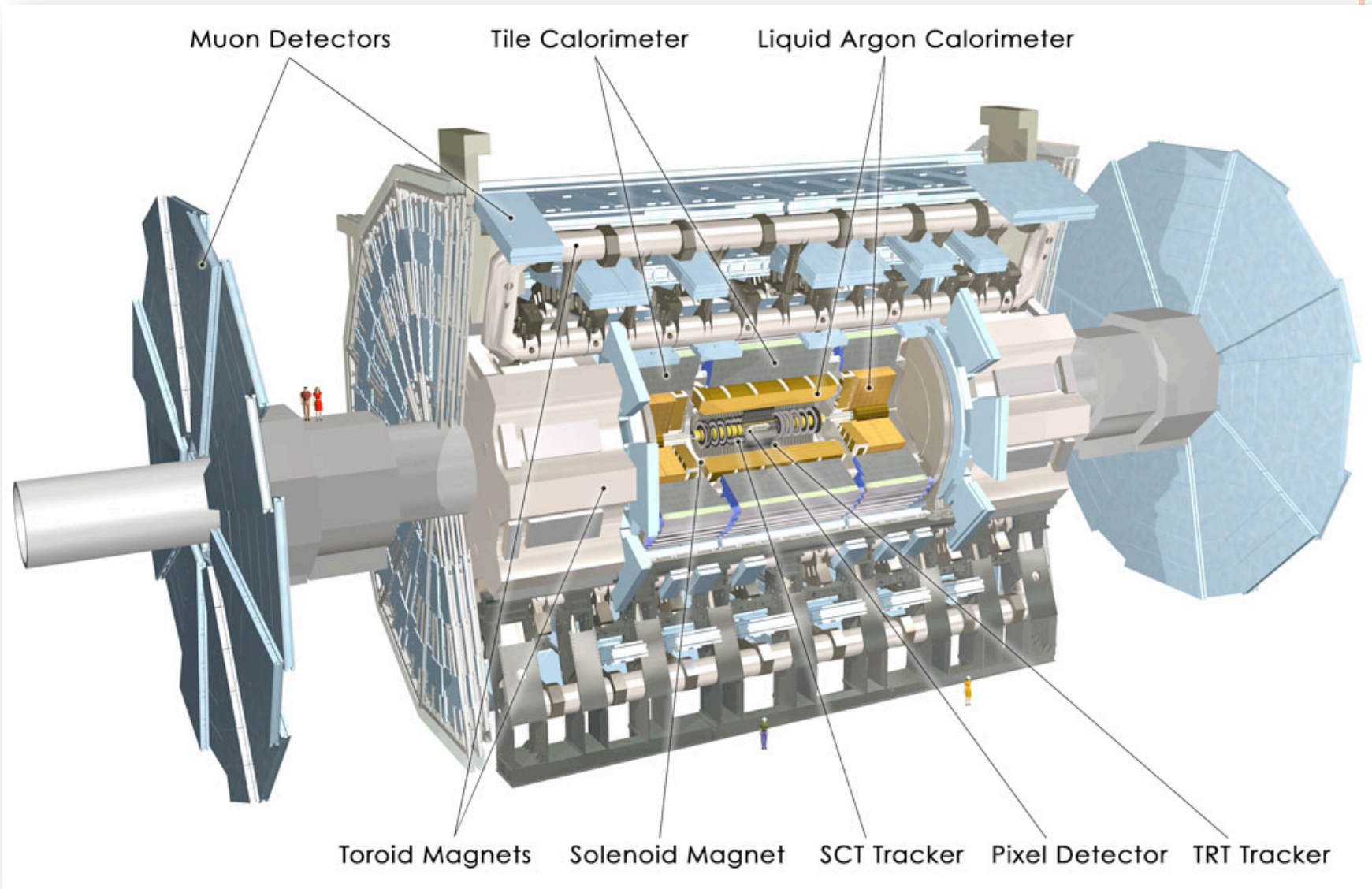
Why 3 quark and lepton families?

Precision b- and top physics

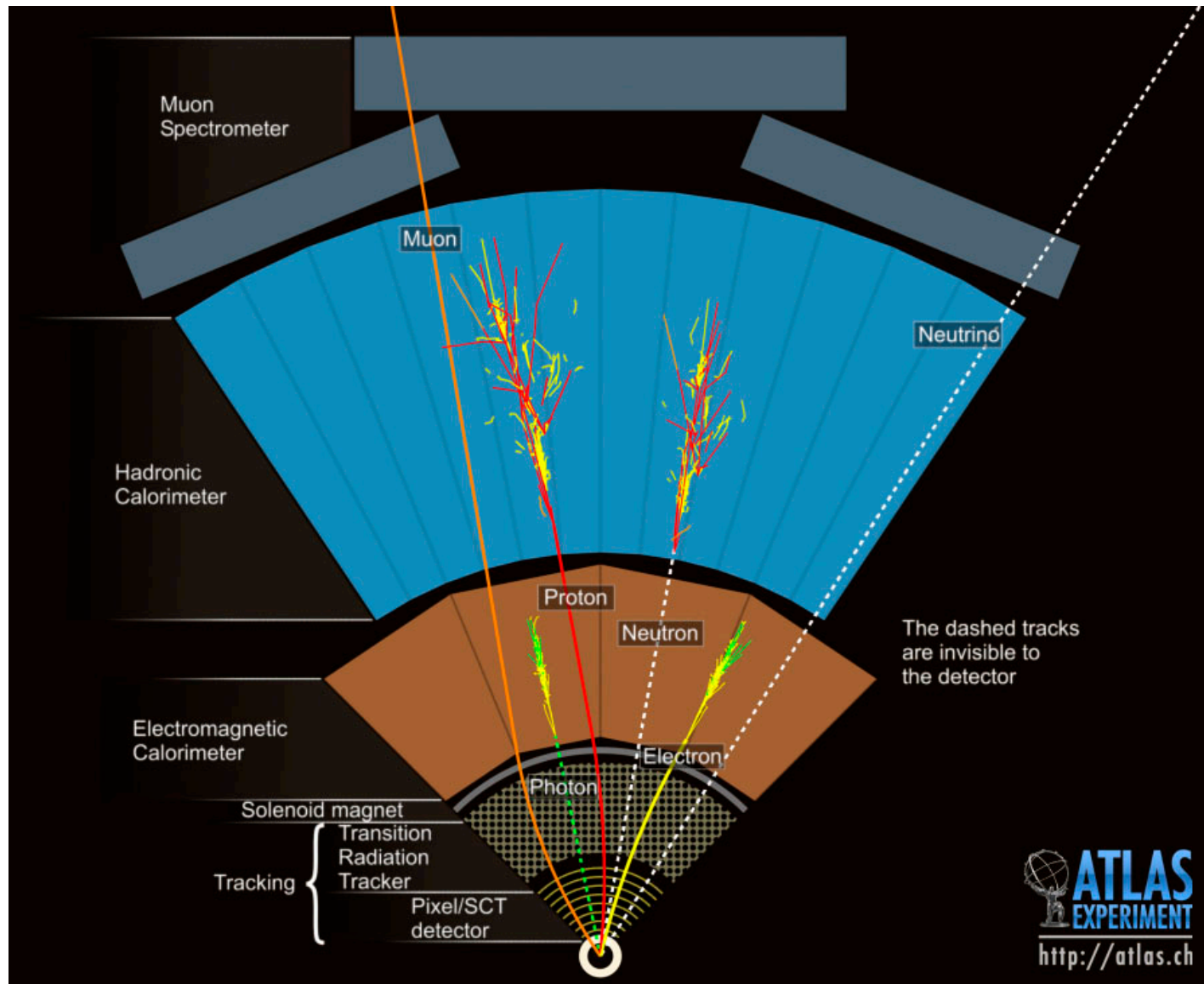
...



# ATLAS

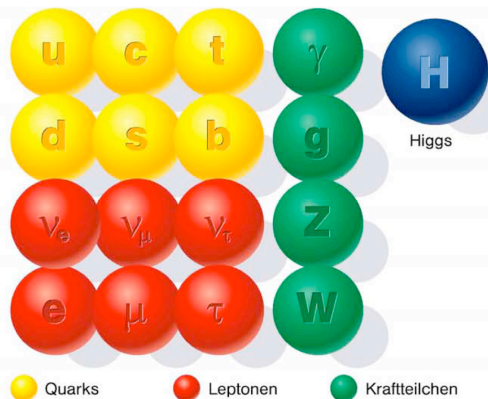


# ATLAS PARTICLE ID

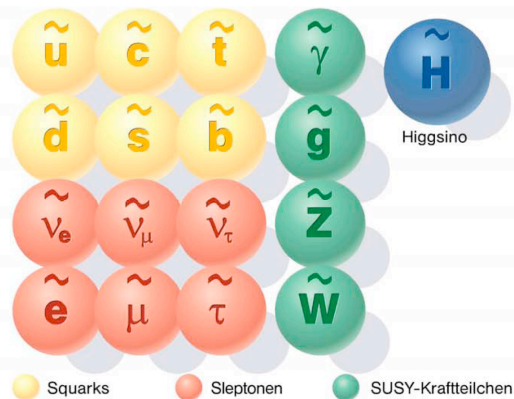


# SUPERSYMMETRY (SUSY)

## Standard Model



## SUSY partners



Differ with  $\frac{1}{2}$  unit spin  
Here consider N=1 SUSY  
particle per SM particle

## Why Supersymmetry?

Hierarchy problem  $\text{Susy} \sim \text{O}(\text{TeV})$   
Dark matter candidate (perhaps)  
Additional source of CP violation  
Unification  
EW symmetry breaking

Mass states  $\tilde{\chi}_i^0 = \sim$  linear  
combinations of  $\tilde{H}$ ,  $\tilde{B}$ ,  $\tilde{W}^0$   
 $\tilde{\chi}_1^0$  is the lightest of these states

Supersymmetry must be broken  
MSSM > 120 parameters  
Or provided model of SUSY breaking  
SUGRA, GMSB, AMSB



# SOME CONSTRAINED SUSY MODELS

By providing a model of how SUSY is broken, the number of parameters (100+ in MSSM) can be largely reduced.

## Gravity mediated: mSugra (4+1 sign)

LSP can be  $\tilde{\chi}_1^0$ ,  $\tilde{G}$ ,  $(\tilde{\tau})$ , ...

$m_{\tilde{G}} : 1 \text{ GeV} - 1 \text{ TeV}$

$\tilde{G}$  plays no role in accelerator pheno

## CMSSM, milder assumptions than mSugra

unified scalar masses, gaugino masses, A..

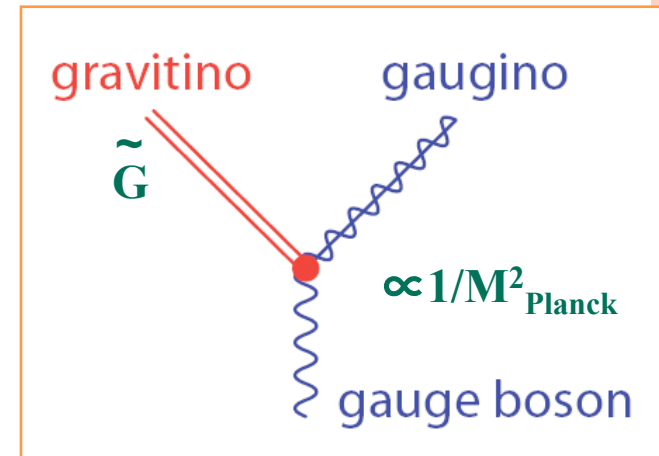
## Gauge Mediated SUSY Breaking

LSP is  $\tilde{G}$  (SUSY partner of graviton)

R-parity needs not to be conserved for  $\tilde{G}$  WDM  $m_{\tilde{G}} < \sim 1 \text{ GeV}$ ,

Lifetime of NLSP gives handle on SUSY breaking scale ...

Phenomenology dependent on NLSP =

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma \quad \tilde{\ell}_R \rightarrow \tilde{G} \ell$$


# SUSY, R-PARITY & COSMOLOGY

R parity introduced to force proton stability

$R = +1$  for SM and  $R = -1$  for SUSY

If R parity is conserved

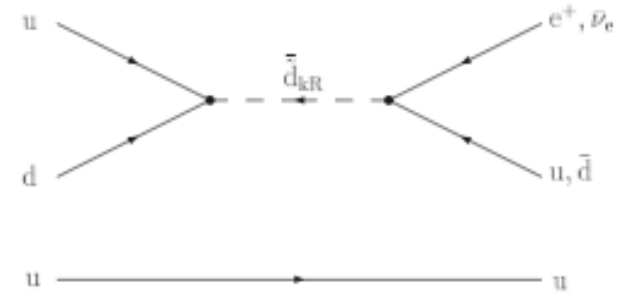
Susy pair production

LSP is stable

neutralino LSP or gravitino LSP  $\Rightarrow$  NLSP relevant (GMSB)

R parity violated

- RPV couplings small from exp. data
  - $\Rightarrow$  SUSY pair production is anyway a good approximation
- violation **can be large enough** so that LSP decays inside detector
- violation **can be small enough** that at accelerator based experiments cannot distinguish b/w RPV and R parity is conserved.
- in any case relevant to cosmology
- but not necessarily relevant to explain today's dark matter



# SUSY PRODUCTION AT LHC

Production at LHC dominated by strong interacting particle:

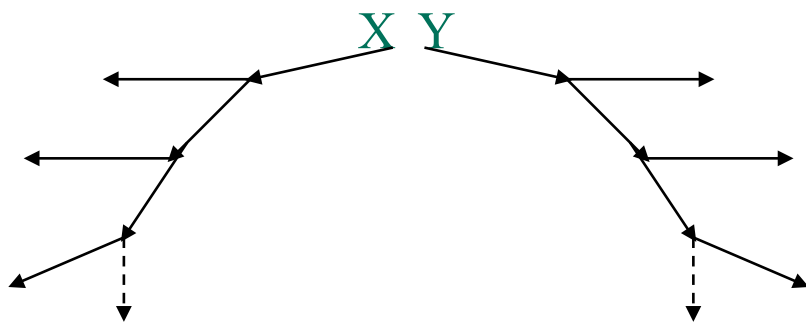
$$\tilde{q}\tilde{q} \quad \tilde{q}\tilde{g} \quad \tilde{g}\tilde{g}$$

Mass hierarchy strongly model-dependent

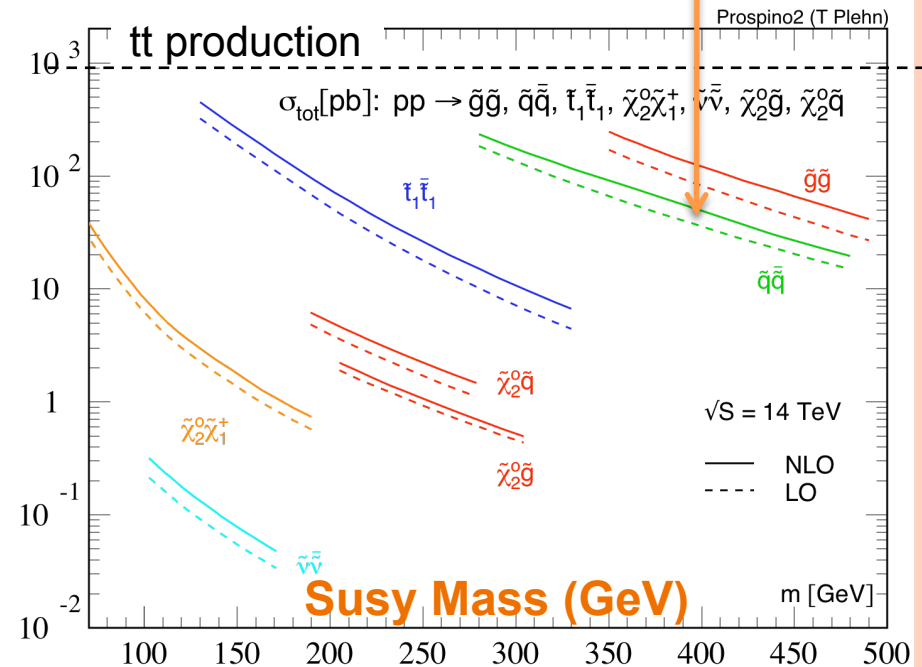
Or  $\tilde{\chi}_i \tilde{\chi}_i$  if  $m(\tilde{q}), m(\tilde{g}) \gg \sim \sqrt{s}/6$  (cf Tevatron, LEP)

R-parity is conserved\* sparticles are pair produced  $pp \rightarrow \tilde{X}\tilde{Y}$

Potentially long decays chains:



Tevatron limits on  $\tilde{g}, \tilde{q}$  masses



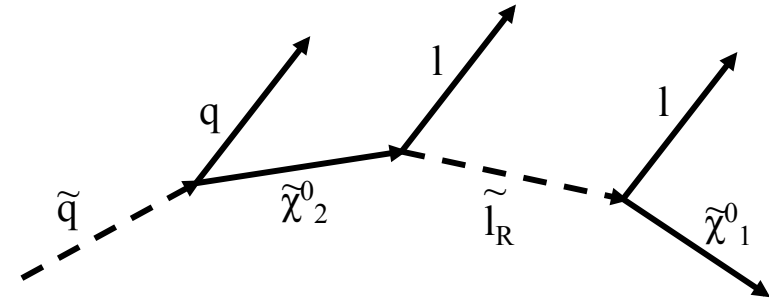
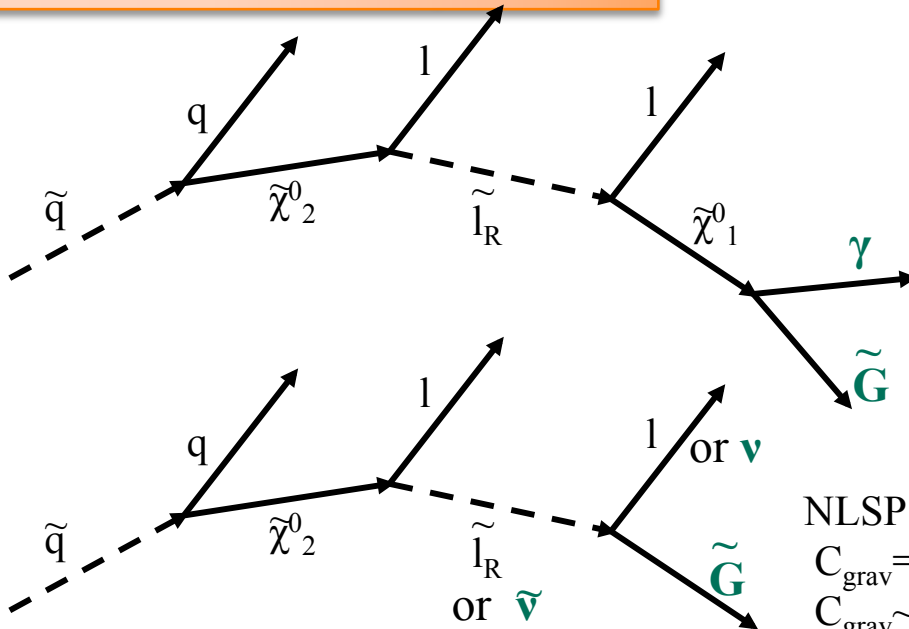
$\sigma(\tilde{g}\tilde{g})$  as high as 100 pb

$\sigma(\tilde{q}\tilde{q})$  as high as 50 pb

\* still valid if only mildly violated

# SUSY EXPERIMENTAL SIGNATURES AT LHC

Long decay chains  
Strongly model dependent...  
2 LSP per event  $E_T^{\text{miss}}$  signature  
  
n jets + m leptons +  $E_T^{\text{miss}}$



**GMSB signature with  $E_T^{\text{miss}}$   
alike mSUGRA, but also  
with 2 high energy  $\gamma$ / event  
or 2 high energy  $\tau$**

NLSP lifetime depends on  $C_{\text{grav}}$

$$C_{\text{grav}} = m_{3/2} / m^0_{3/2}$$

$$C_{\text{grav}} \sim 1 \Rightarrow \text{prompt NLSP decay}$$

$C_{\text{grav}} \gg 1 \Rightarrow$  NLSP decay outside the detector

Lifetime measurable if in range mm-km



# ATLAS BENCHMARK POINTS

CMSSM

## SU1 "Coannihilation Region"

$m(\tilde{g}) \sim 830$  GeV  $m(\tilde{q}) \sim 750$  GeV  
 $\tilde{\chi}_1^0$  annihilates with  $\ell$

## SU2 "Focus Point"

$m(\tilde{g}) \sim 860$  GeV  $m(\tilde{q}) \sim 3500$  GeV  
 $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow WW$  enhanced ( $\tilde{H}$  comp.)

## SU3 "Bulk Point"

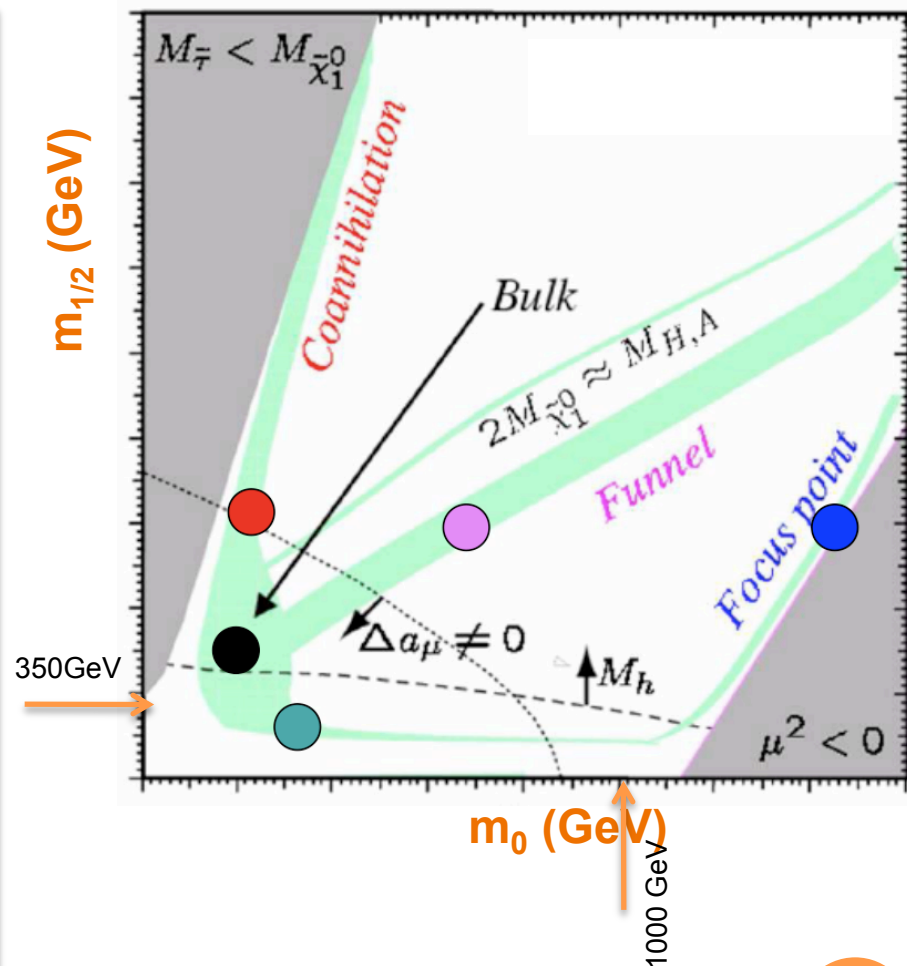
$m(\tilde{g}) \sim 720$  GeV  $m(\tilde{q}) \sim 620$  GeV  
 $\tilde{\chi}_1^0 \tilde{\chi}_1^0$  annihilation via  $\ell$

## SU4 "Low mass"

$m(\tilde{g}) \sim 420$  GeV  $m(\tilde{q}) \sim 420$  GeV  
 Close to Tevatron's bound

## SU6 "Funnel Regions"

$m(\tilde{g}) \sim 900$  GeV  $m(\tilde{q}) \sim 870$  GeV  
 $\tau$  decays dominates



Strong constraints from

- LEP + Tevatron direct searches
- WMAP,  $m_{h_0} > 114$  GeV,  $g_\mu - 2$ ,  $b \rightarrow s \gamma$

# SEARCH CHANNELS

## 0-lepton + n jets + $E_T^{\text{miss}}$ search n=4:

jets /  $E_T^{\text{miss}}$  triggers  
 $p_T(\text{jet1}) > 100 \text{ GeV}$ ,  $p_T(\text{jet4}) > 50 \text{ GeV}$   
 $E_T^{\text{miss}} > 100 \text{ GeV}$ ,  $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$   
 $S_T > 0.2$   
 $E_T^{\text{miss}}$  not aligned with jet1-3  
 e/ $\mu$  veto  
 $M_{\text{eff}} > 800 \text{ GeV}$

Also n=2, 3

## 1-lepton + n jets + $E_T^{\text{miss}}$ search n=4:

1 e/ $\mu$  20 GeV, 2<sup>nd</sup> lepton veto  
 lepton/ jets /  $E_T^{\text{miss}}$  triggers  
 $p_T(\text{jet1}) > 100 \text{ GeV}$ ,  $p_T(\text{jet4}) > 50 \text{ GeV}$   
 $E_T^{\text{miss}} > 100 \text{ GeV}$ ,  $E_T^{\text{miss}} > 0.2 M_{\text{eff}}$   
 $S_T > 0.2$   
 $M_T > 100 \text{ GeV}$   
 $M_{\text{eff}} > 800 \text{ GeV}$

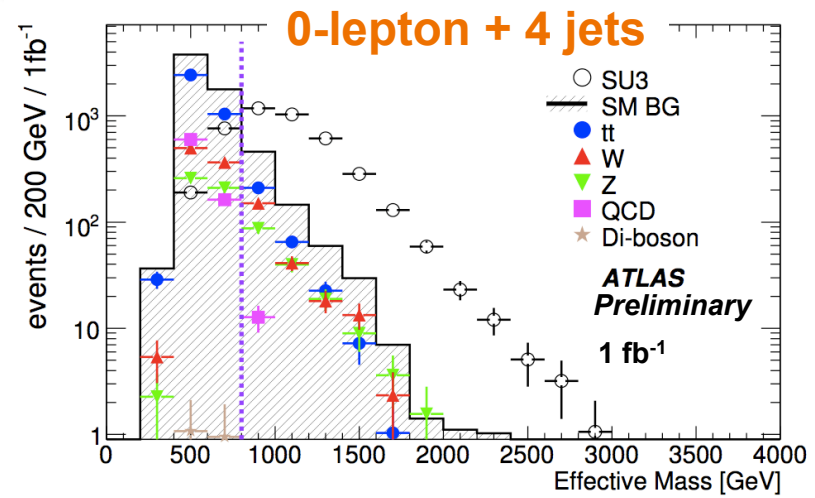
Also n=2, 3 studied

## 0-lepton backgrounds

QCD with fake  $E_T^{\text{miss}}$

$t\bar{t} \rightarrow \text{jets}$ ,  $Z \rightarrow \nu\nu$

$W \rightarrow \ell \nu$  non reconstructed  $\ell$



## 1-lepton backgrounds

QCD with fake  $E_T^{\text{miss}}$  + fake lepton

$t\bar{t} \rightarrow \ell + \text{jets}$ ,

$W \rightarrow \ell \nu + \text{jets}$

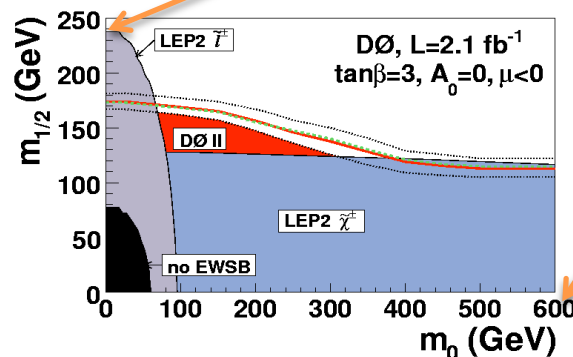
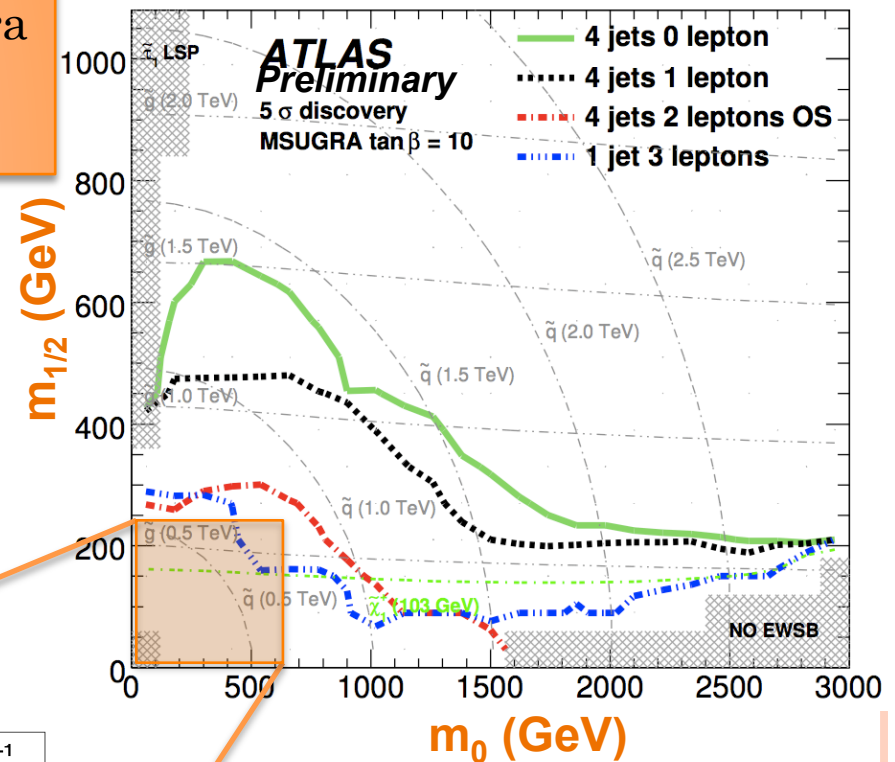
Potentially easier to understand 14 than 0-lepton backgrounds

# ATLAS POTENTIAL FOR DISCOVERY

Discovery potential illustrated in mSugra  
R is conserved  
Detailed cuts depend on N leptons

**Significance estimate includes**  
systematic uncertainties from:  
QCD background estimate 50%  
tt, V+jets, VV+jets 20%  
Motivated by techniques for  
data driven estimation of backgrounds

$L = 1 \text{ fb}^{-1} = 2009 ?$

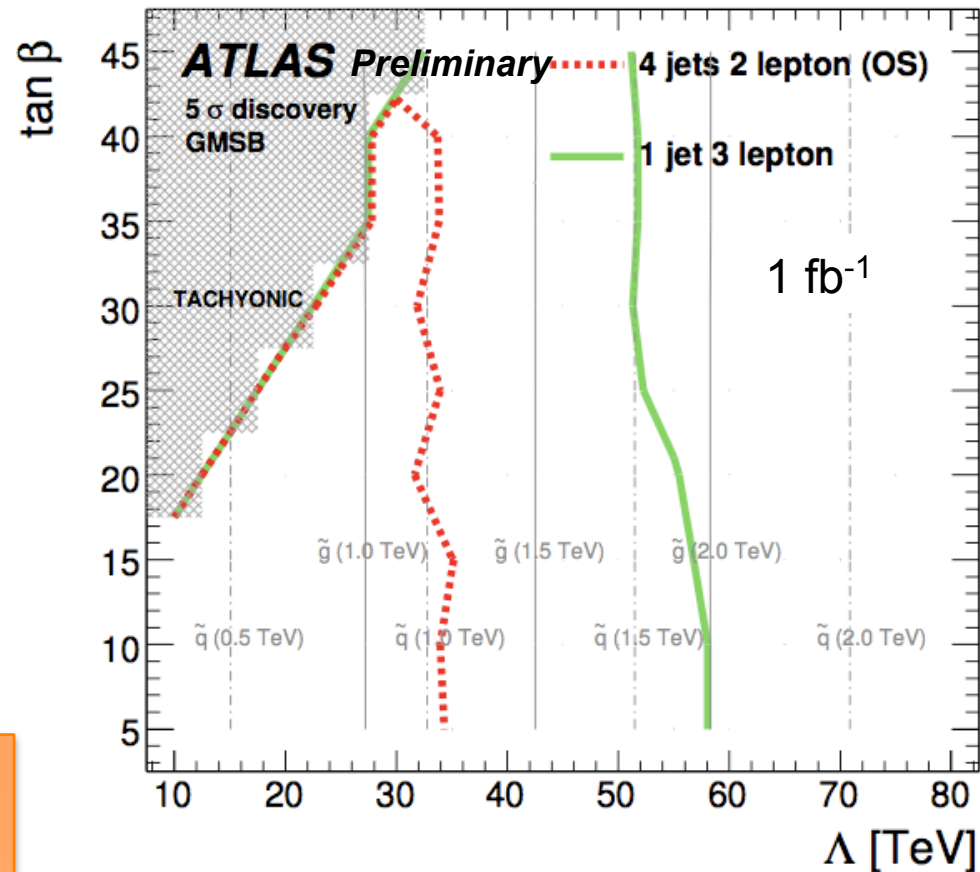


D0 / Tevatron  $2 \text{ fb}^{-1}$

# ATLAS POTENTIAL FOR DISCOVERY / GMSB

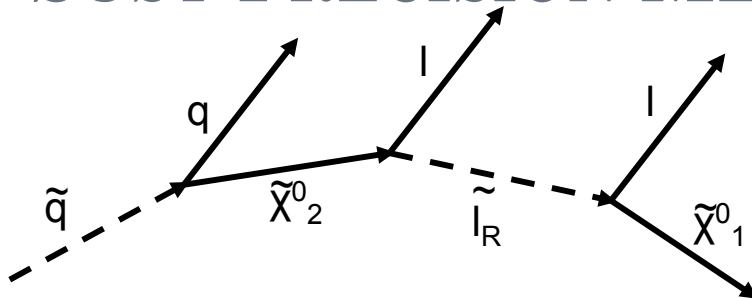
Prompt NLSP decay  
in GMSB  $\tilde{\ell} \rightarrow \tilde{G} \ell$

GMSB scan, NLSP = slepton  
2 leptons per GMSB event





# SUSY PRECISION MEASUREMENTS



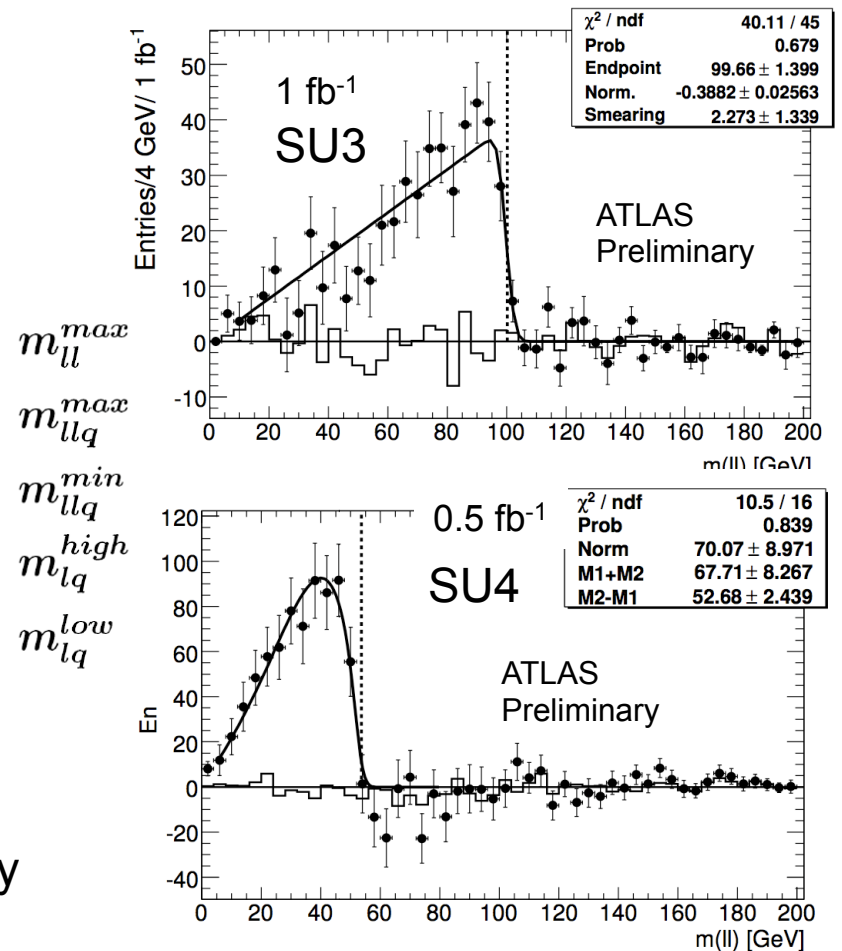
## 1) Extract observables

- $l^+ l^-$  edge
- $l^+ l^- q$  edge
- $l^+ l^- q$  threshold
- $l^\pm q$  high-edge
- $l^\pm q$  low-edge

## 2) Fit Susy masses to observed edges

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{q}_L$  ( $\tilde{q}_R$ ) can be extracted  
Requires some knowledge of mass hierarchy

## 3) Fit model parameter to masses

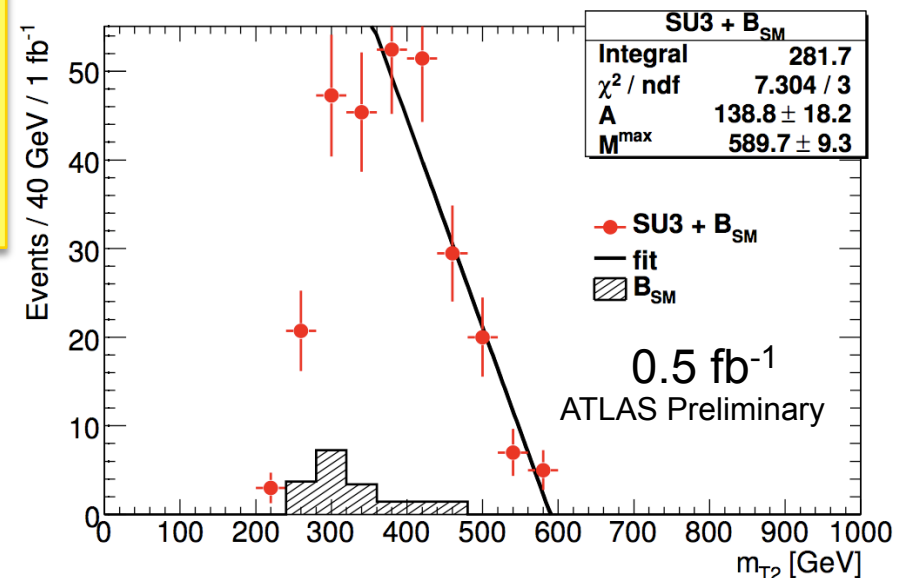


# HOW TO EXTRACT MASS OF $\tilde{q}_R$

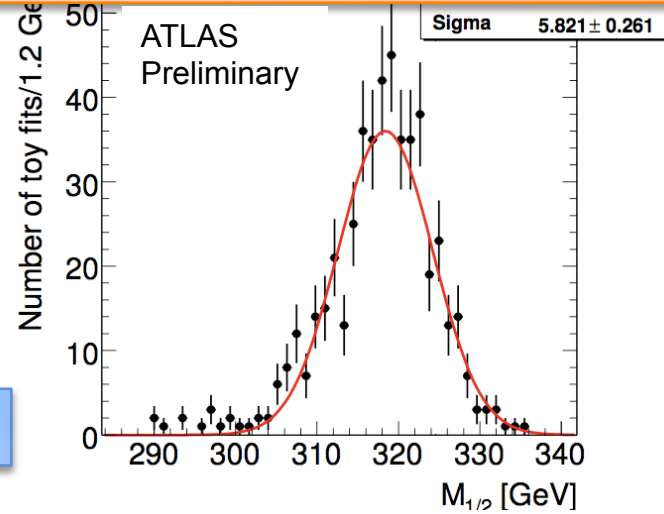
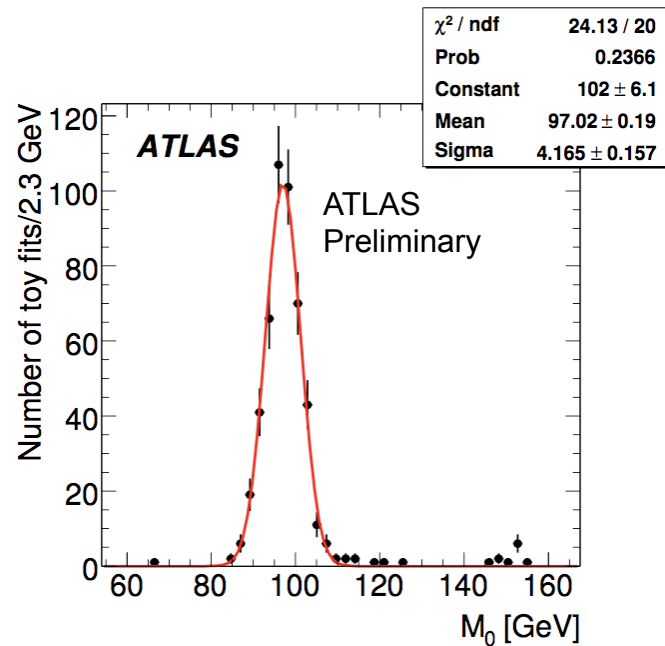
SUSY events  $pp \rightarrow \tilde{q}_R \tilde{q}_R$  5% in SU4 and 10% in SU3  
with decay:  $\tilde{q}_R \rightarrow \tilde{\chi}_1^0 q$

- $E_T^{\text{miss}} > \max(200 \text{ GeV}, 0.25 M_{\text{eff}})$
- $M_{\text{eff}} > 500 \text{ GeV}$
- 2 Jets with  $p_T > \max(200 \text{ GeV}, 0.25 M_{\text{eff}})$
- Jets have  $|\eta| < 1$ ,  $\Delta R > 1$
- No additional jets with  $p_T > \min(200 \text{ GeV}, 0.15 M_{\text{eff}})$
- No isolated leptons, no b-jets
- $S_T > 0.2$

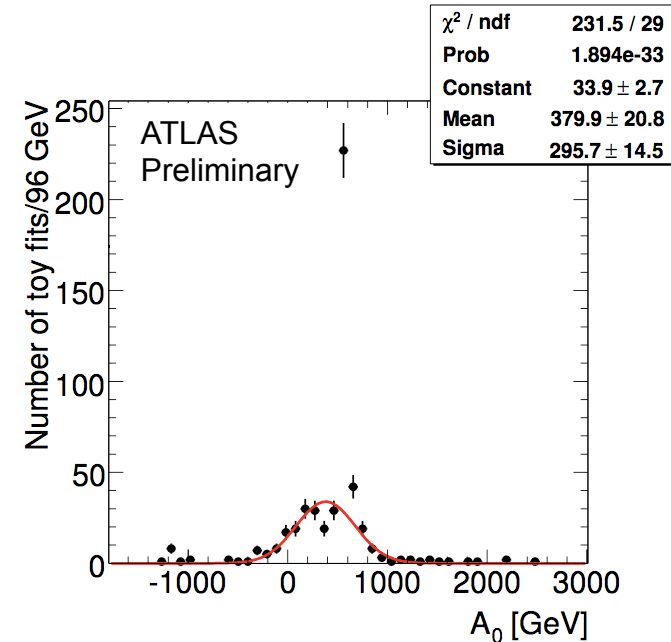
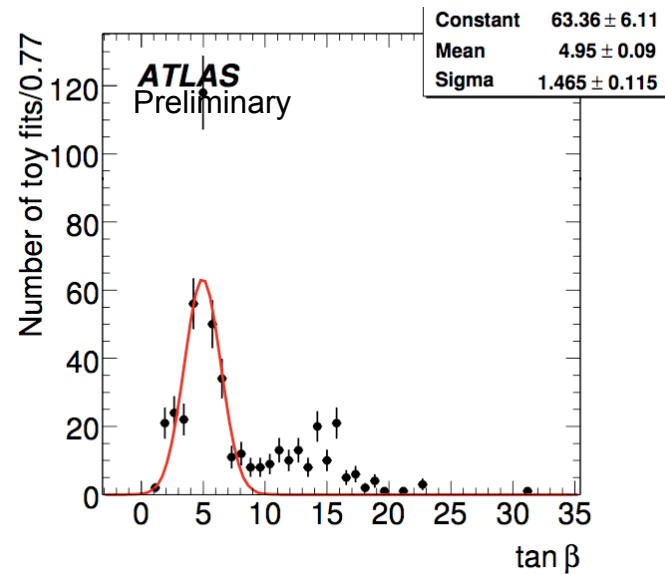
Extract  $m_{\tilde{q}_R}$  from  
 $m_{T2}$  fit



Generate pseudo-experiments with the set of observables from kine edges with resolutions corresponding to expected experimental accuracies at 1fb-1



SU3

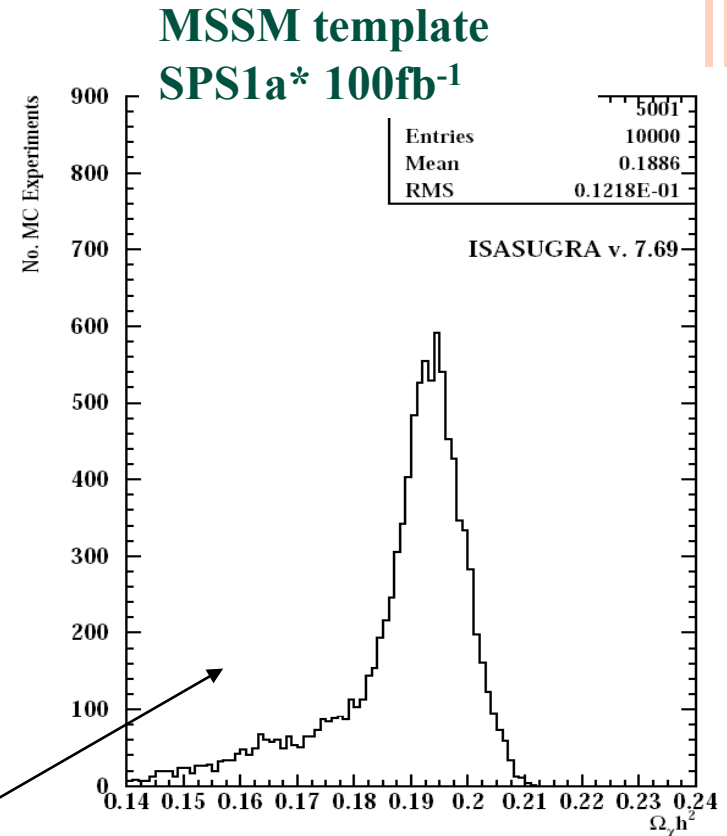


In this example tan beta not well constrained, nor sgn mu. Does not include independent constraints on Higgs sector

# EG. SUSY MEASUREMENTS AND COSMOLOGY

- How to relate the model independent observables to the model is the tricky part
- Keep template models consistent with the model independent measurements
- From the surviving models compute expectation of DM relic density
- Which one are compatible with cosmological observations?

Distribution of relic density for the surviving models



M.M. Nojiri, G. Polesello,  
D. Tovey JHEP 05 (2004)

20

\* SPS1a ~ similar to bulk region



# SUSY WITH PHOTONS

GMSB with  $\tilde{\chi}_1^0$  NLSP  
Lifetime of NLSP determined by  
model parameter  $C_{\text{grav}}$

	$c\tau$	$C_{\text{grav}}$
"Prompt"	1.1 mm	
GMSB2	95 cm	
GMSB3	3.2 m	

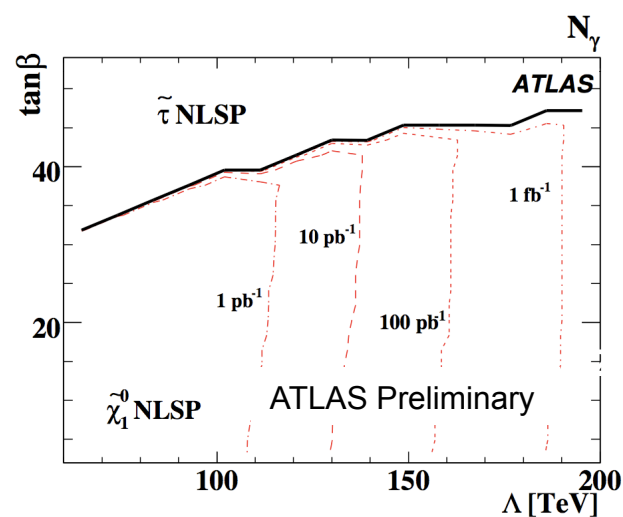
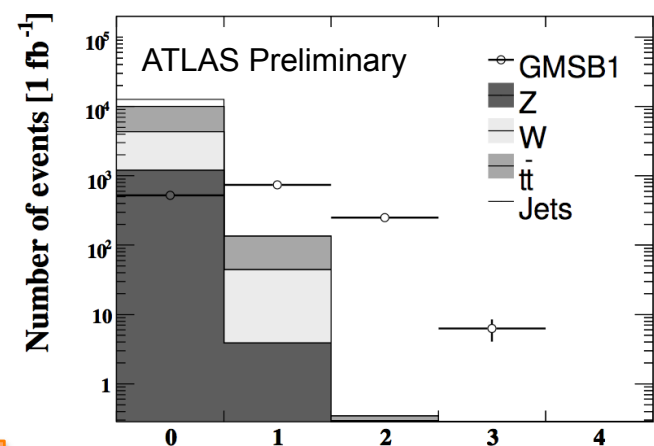
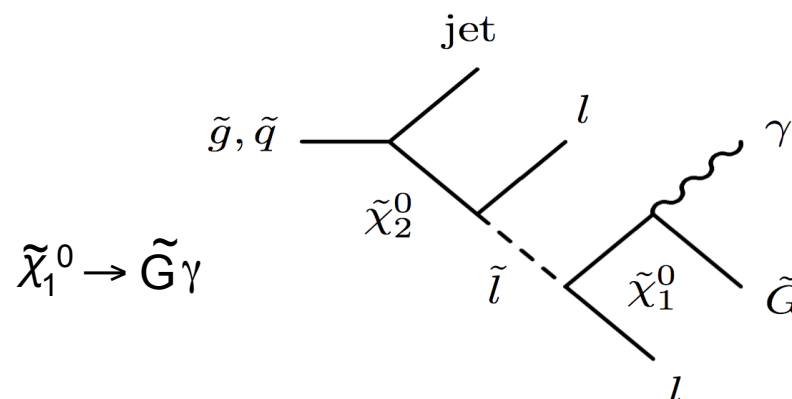
## Selections for prompt $\gamma$ SUSY

### 1) "SUSY-style"

$p_{\text{T}}(\text{jet1}) > 100 \text{ GeV}$ ,  $p_{\text{T}}(\text{jet4}) > 50 \text{ GeV}$   
 $E_{\text{T}}^{\text{miss}} > 100 \text{ GeV}$ ,  $E_{\text{T}}^{\text{miss}} > 0.2 \text{ Meff}$

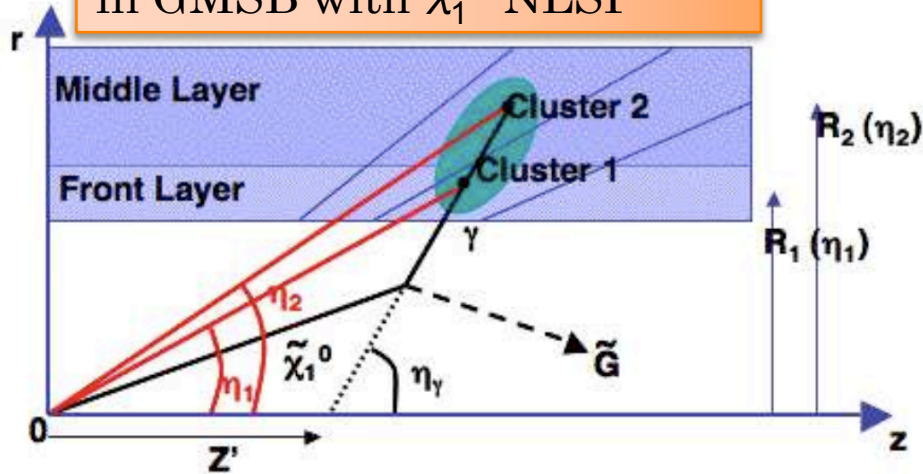
### 2) + 1 or 2 isolated $\gamma$ with $p_{\text{T}} > 20 \text{ GeV}$ , $|\eta| < 2.5$

48.9 % (16.4%) of GMSB1 have 1 (2) photons  
with  $p_{\text{T}} > 20 \text{ GeV}$ ,  $|\eta| < 2.5$   
Photon ID efficiency  $\sim 65\%$

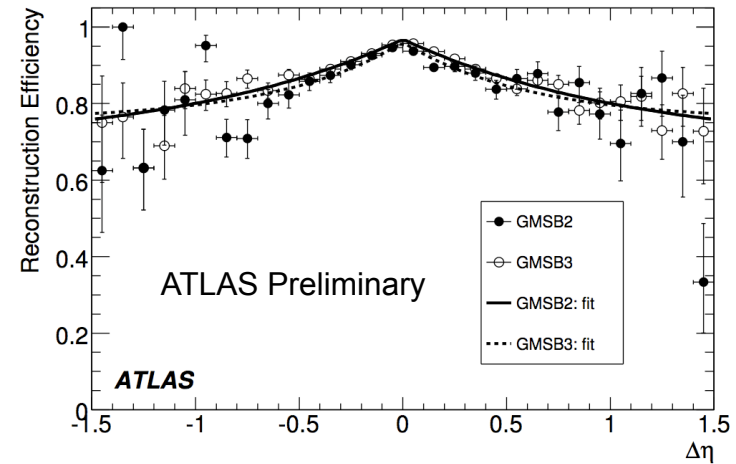


# SEARCH FOR LONG LIVED SUSY PARTICLES

Non-pointing  $\gamma$  from  $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$   
in GMSB with  $\tilde{\chi}_1^0$  NLSP

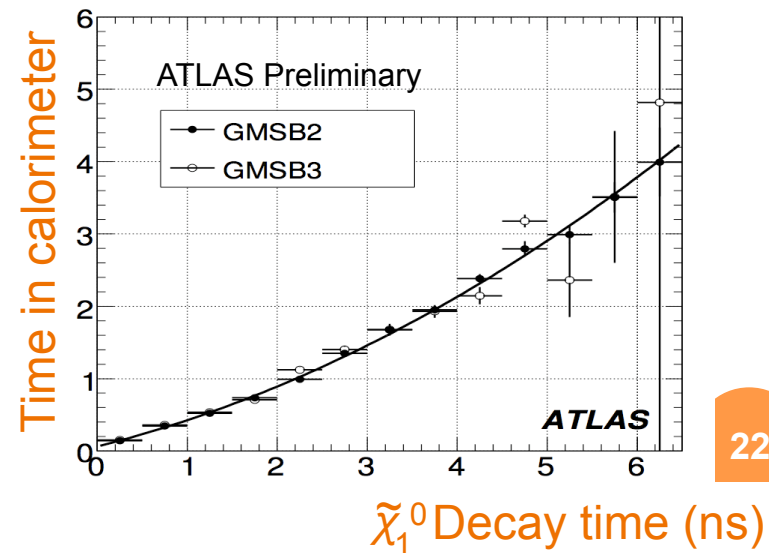


non-pointing  $\gamma$  efficiency



Measure lifetime of  $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$  from:  
i)  $Z'$  distribution  
ii) Calorimeter timing

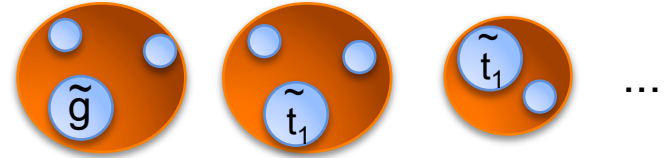
In both methods,  
careful calibration &  
study of biases necessary



# R-HADRON AND STABLE SLEPTONS

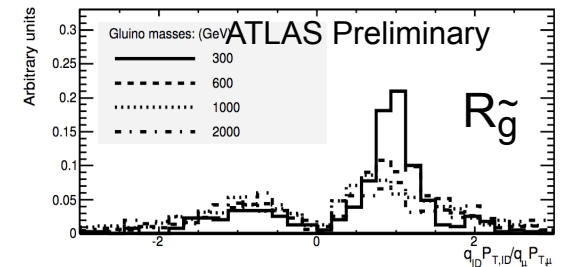
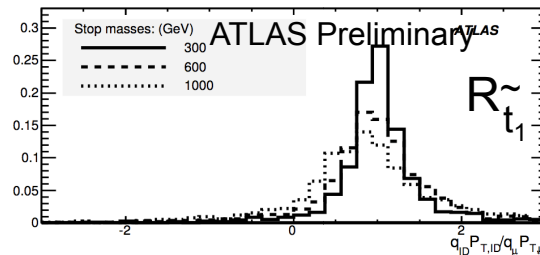
R-Hadron = supersymmetric hadrons

- Split SUSY with stable  $\tilde{g}$
- SUSY with  $\tilde{t}_1$  NLSP and  $\tilde{G}$  LSP



## Events / fb<sup>-1</sup> After selections

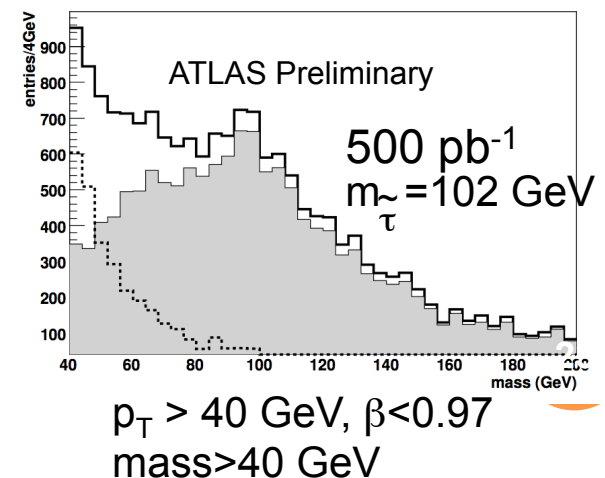
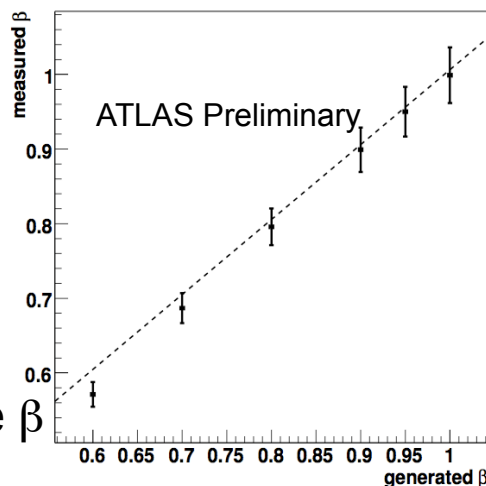
600 GeV $R_{\tilde{g}}$	2700
1000 GeV $R_{\tilde{g}}$	10.7
2000 GeV $R_{\tilde{g}}$	0.013
1000 GeV $R_{\tilde{t}}$	0.1
SM Background	1.7



$$q^D p_T^D / q^u p_T^u$$

Metastable sleptons  
in GMSB  $\tilde{\tau} \rightarrow \tilde{G} \tau$

Measured vs true  $\beta$   
at L2 trigger



# CONCLUSION AND OUTLOOK

ATLAS should be able to discover Supersymmetry whether RPV is violated or not up to O(TeV) scale.

Sensitive to signatures such as:

multi-jet +  $E_T^{\text{miss}}$  + n leptons

n  $\gamma$  +  $E_T^{\text{miss}}$

$\tau$  + jet

long lived sleptons or R-hadrons

Sensitive to a wide range of scenarios, with  $\tilde{g}$  and/or  $\tilde{q}$  masses up 1-2 TeV

Get a map of states where Susy (or sthg else) is observed and constrain model.

Consequence and consistency for cosmology

# BACKUP SLIDES



# SOME DEFINITIONS FOR SUSY ANALYSES

$$\text{Effective Mass } M_{\text{eff}} = \sum_{1-4} p_T^{\text{jet}} + \sum p_T^{\text{leptons}} + E_T^{\text{miss}}$$

$$\text{Transverse Sphericity } S_T = 2 \lambda_2 / (\lambda_1 + \lambda_2)$$

$$2 \times 2 \text{ transverse sphericity tensor: } S_{ij} = \sum_k p_{ki} p_{kj} \\ (\text{sum runs over jets and lepton})$$

$$\text{Transverse Mass } M_T = (m^\alpha)^2 + \mathbf{p}_T^\alpha \cdot \mathbf{p}_T^{\text{miss}}$$

stransverse Mass =

$$m_{T2}^2(\mathbf{p}_T^\alpha, \mathbf{p}_T^\beta, \mathbf{p}_T^{\text{miss}}, m_\alpha, m_\beta, m_\chi) \equiv \min_{\mathbf{q}_T^{(1)} + \mathbf{q}_T^{(2)} = \mathbf{p}_T^{\text{miss}}} \left[ \max \left\{ M_T^2(\mathbf{p}_T^\alpha, \mathbf{q}_T^{(1)}; m_\alpha, m_\chi), M_T^2(\mathbf{p}_T^\beta, \mathbf{q}_T^{(2)}; m_\beta, m_\chi) \right\} \right]$$



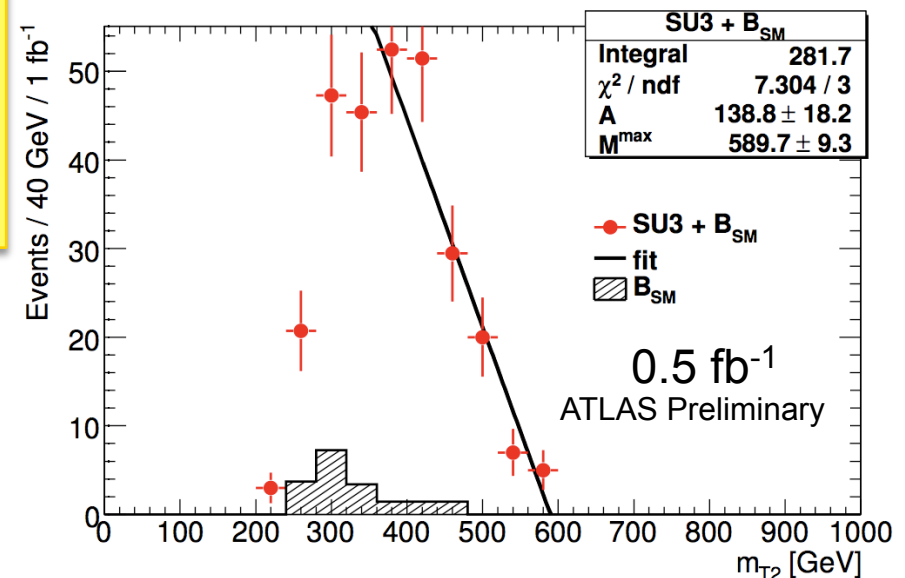


# HOW TO EXTRACT MASS OF $\tilde{q}_R$

SUSY events  $pp \rightarrow \tilde{q}_R \tilde{q}_R$  5% in SU4 and 10% in SU3  
with decay:  $\tilde{q}_R \rightarrow \tilde{\chi}_1^0 q$

- $E_T^{\text{miss}} > \max(200 \text{ GeV}, 0.25 M_{\text{eff}})$
- $M_{\text{eff}} > 500 \text{ GeV}$
- 2 Jets with  $p_T > \max(200 \text{ GeV}, 0.25 M_{\text{eff}})$
- Jets have  $|\eta| < 1$ ,  $\Delta R > 1$
- No additional jets with  $p_T > \min(200 \text{ GeV}, 0.15 M_{\text{eff}})$
- No isolated leptons, no b-jets
- $S_T > 0.2$

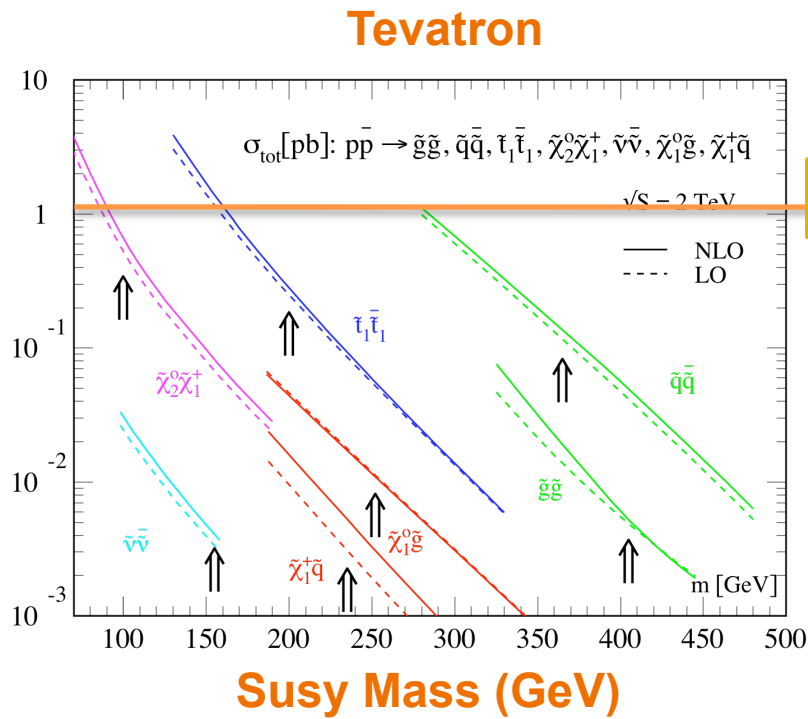
Extract  $m_{\tilde{q}_R}$  from  
 $m_{T2}$  fit



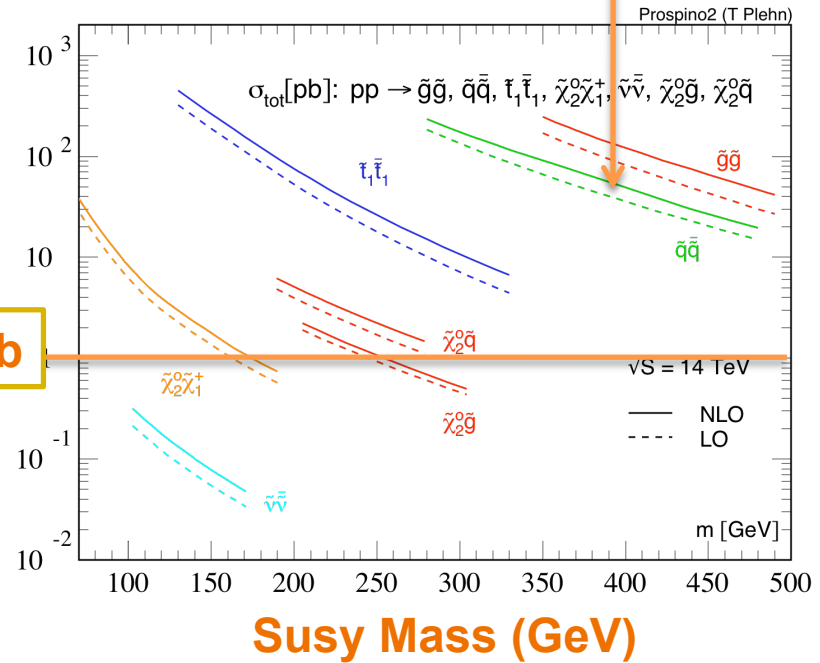
# SUSY PRODUCTION AT LHC

**Tevatron**  
limit on g, q masses

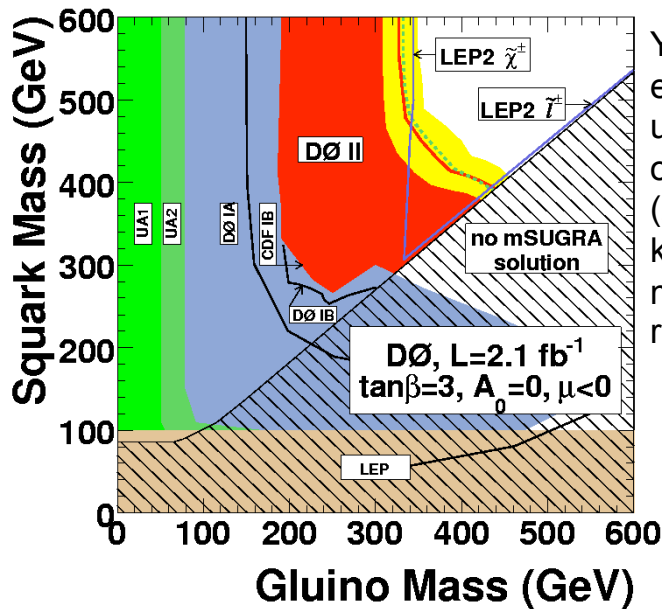
**LHC**



**1 pb**

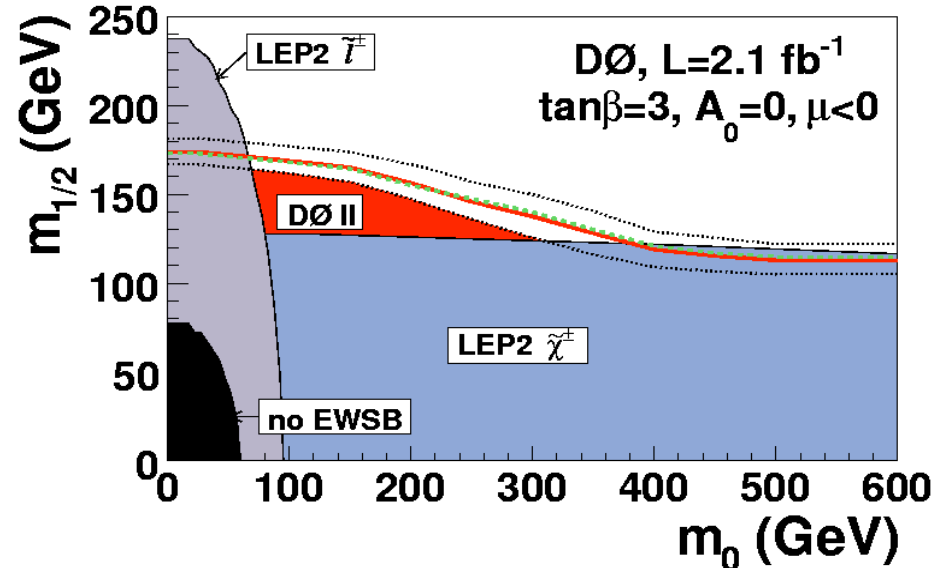


# SQUARKS, GLUINOS LIMITS FROM TEVATRON



Yellow band shows the huge effect of PDF (and RF scale) uncertainty (CTEQ6.1M) on the signal NLO cross section (25 to 75%) due to the poor knowledge of gluon at high  $x$ : more constraints will come from recent QCD results from DØ

Results can also be shown as a function of the mSUGRA parameters



	M(Gluino)		M(Squark)	
	obs.	exp.	obs.	exp.
$\mathcal{R}(\min)$	308	312	379	377
$\mathcal{R}(\text{nom})$	327	332	392	391
$\mathcal{R}(\max)$	349	354	406	404

Most conservative case: signal cross section diminished by its uncertainty due to PDF/RF scale:

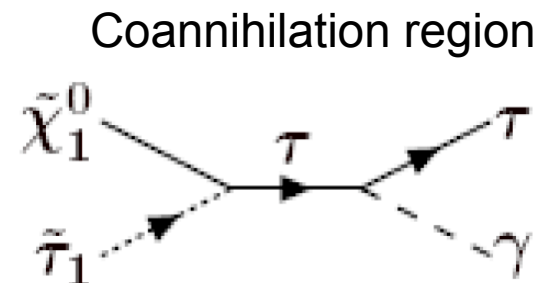
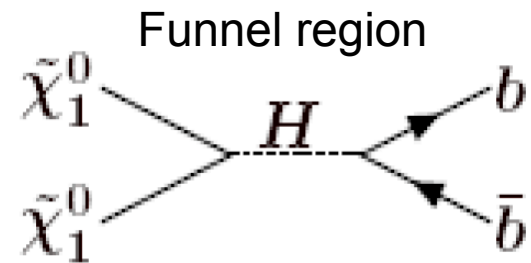
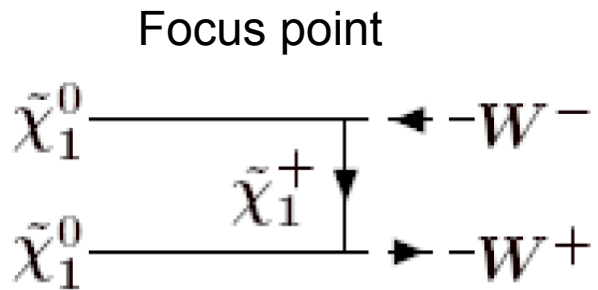
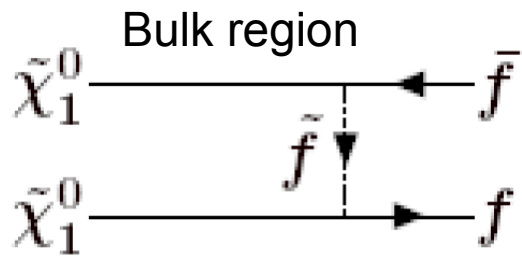
For  $M_{\text{squark}} = M_{\text{gluino}}$ ,  $M(\text{sq-gl}) > 390 \text{ GeV}$

LEP2 limits improved for  $m_0$  between 70 and 300 GeV

# ATLAS mSUGRA BENCHMARK POINTS

- SU1  $m_0 = 70$  GeV,  $m_{1/2} = 350$  GeV,  $A_0 = 0$ ,  $\tan\beta = 10$ ,  $\mu > 0$ . Coannihilation region where  $\tilde{\chi}_1^0$  annihilate with near-degenerate  $\tilde{\ell}$ .
- SU2  $m_0 = 3550$  GeV,  $m_{1/2} = 300$  GeV,  $A_0 = 0$ ,  $\tan\beta = 10$ ,  $\mu > 0$ . Focus point region near the boundary where  $\mu^2 < 0$ . This is the only region in mSUGRA where the  $\tilde{\chi}_1^0$  has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as  $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow WW$ .
- SU3  $m_0 = 100$  GeV,  $m_{1/2} = 300$  GeV,  $A_0 = -300$  GeV,  $\tan\beta = 6$ ,  $\mu > 0$ . Bulk region: LSP annihilation happens through the exchange of light sleptons.
- SU4  $m_0 = 200$  GeV,  $m_{1/2} = 160$  GeV,  $A_0 = -400$  GeV,  $\tan\beta = 10$ ,  $\mu > 0$ . Low mass point close to Tevatron bound.
- SU6  $m_0 = 320$  GeV,  $m_{1/2} = 375$  GeV,  $A_0 = 0$ ,  $\tan\beta = 50$ ,  $\mu > 0$ . The funnel region where  $2m_{\tilde{\chi}_1^0} \approx m_A$ . Since  $\tan\beta \gg 1$ , the width of the pseudoscalar Higgs boson  $A$  is large and  $\tau$  decays dominate.
- SU8.1  $m_0 = 210$  GeV,  $m_{1/2} = 360$  GeV,  $A_0 = 0$ ,  $\tan\beta = 40$ ,  $\mu > 0$ . Variant of coannihilation region with  $\tan\beta \gg 1$ , so that only  $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$  is small.
- SU9  $m_0 = 300$  GeV,  $m_{1/2} = 425$  GeV,  $A_0 = 20$ ,  $\tan\beta = 20$ ,  $\mu > 0$ . Point in the bulk region with enhanced Higgs production





Difficult to observe at LHC, very soft taus due to small  $\Delta M(\tau, \tilde{\chi}_1^0)$

$\tilde{\chi}_1^0$  relic density  $\sim 1/\langle\sigma v\rangle$

$\Rightarrow$  need to know the couplings

Strong constraints from

- LEP + Tevatron direct searches
- WMAP,  $m_{h^0} > 114$  GeV,  $g_\mu - 2$ ,  $b \rightarrow s\gamma$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tau \tau$   $\tilde{\chi}_1^0 \tilde{\tau} \rightarrow \tau \gamma$

